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Effects of Peak Pressure and Energy of Impulses (Reprint)

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Peak pressure has been one of the key parameters of impulse noise used to assess the hazard to hearing. It is used in most international noise exposure limits. France uses an A-weighted energy limit. There is a rough correspondence between peak pressure and the hazard to hearing for a given type of impulse noise. However, when the effects of different types of impulses are compared, this correspondence breaks down. One of the alternate measures of impulse intensity is weighted energy. Weighted energy is appealing for a number of reasons. It does not depend on details of the pressure-time history such as the peak pressure and the more common duration measures. It should be easier to integrate with continuous or intermittent noise standards. It should make it easier to use standard hearing protector attenuation to estimate the hazard when a specific hearing protector is worn. Results of previously published articles and reports will be discussed. These reports lead to the conclusion that weighted energy is a more potent determiner of hearing hazard than peak pressure if spectral effects are controlled.

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Effects of peak pressure and energy of impulses

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Peak pressure has been one of the key parameters of impulse noise used to assess the hazard to hearing. It is used in most international noise exposure limits. France uses an A-weighted energy limit. There is a rough correspondence between peak pressure and the hazard to hearing for a given type of impulse noise. However, when the effects of different types of impulses are compared, this correspondence breaks down. One of the alternate measures of impulse intensity is weighted energy. Weighted energy is appealing for a number of reasons. It does not depend on details of the pressure-time history such as the peak pressure and the more common duration measures. It should be easier to integrate with continuous or intermittent noise standards. It would make it easier to use standard hearing protector attenuation to estimate the hazard when a specific hearing protector is worn. Results of previously published articles and reports will be discussed. These reports lead to the conclusion that weighted energy is a more potent determiner of hearing hazard than peak pressure if spectral effects are controlled.

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INTRODUCTION

Peak pressure has been one of the key parameters of impulse noise used to assess the hazard to hearing (Coles *et al.*, 1968). It is used in most international noise exposure limits (Smoorenburg, 1987). France, for example uses an A-weighted energy limit. There is a rough correspondence between peak pressure and the hazard to hearing for a given type of impulse noise. However, when one compares the effects of different types of impulses, this correspondence breaks down (Price, 1983, 1986a,b). In most cases where impulses of the same peak pressure produce different amounts of injury or where different peak pressures produce the same amount of injury, there are differences in the distribution of acoustic energy across frequencies. These spectral effects are not the topic of this paper, but their existence limits the studies that are relevant to this paper. There is general international agreement that the spectrum of an impulse must be taken into account in any valid impulse noise exposure limit (Smoorenburg, 1987). This strong spectral effect also implies that spectrum must be controlled in comparing the effects of other parameters on the hazard of impulse noise.

One of the alternate measures of impulse intensity is weighted energy. Here, the terms "energy" and "intensity" are used in their common sense rather than their technical meanings. Weighted energy is appealing for several reasons. It does not depend on details of the pressure-time history such as the peak pressure and the more common duration measures. It should be easier to integrate with continuous or intermittent noise standards. Weighted energy would make it easier to use standard measures of hearing protector attenuation to estimate the hazard when a specific hearing protector is worn. Thus if a weighted energy concept could be shown to approximate reality, it would be a useful construct.

The use of energy as a possible indicator of auditory

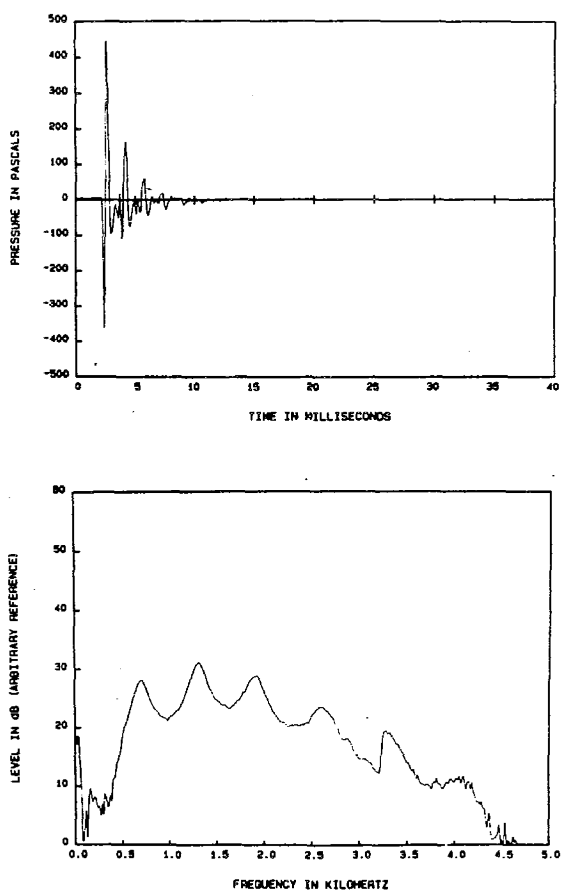

FIG. 1. The high-peak pressure time waveform (upper) and its frequency spectrum (lower).

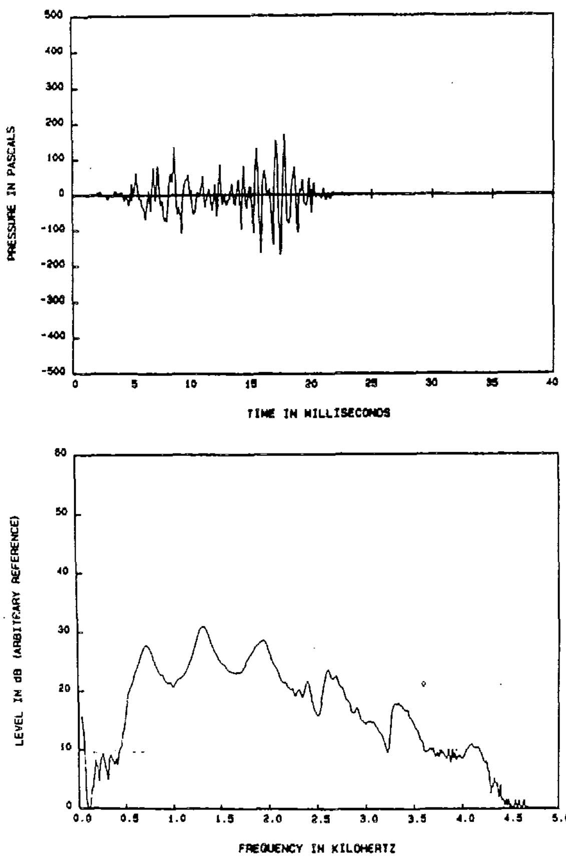

FIG. 2. The low-peak pressure time waveform (upper) and its frequency spectrum (lower).

hazard conjures up the "equal energy hypothesis" (Burns and Robinson, 1970; Atherly and Martin, 1971). When this concept is applied to impulse noise, it can be divided into at least three separately testable hypotheses. First, energy (or weighted energy) can be used to assess the hazard from a single impulse or from the same number of impulses with different characteristics. That is, that energy is an alternative to peak pressure as a measure of intensity, which can be used to estimate the hazard from each individual impulse. Second, the equal energy hypothesis implies a specific trading relation between the number of impulses and intensity, specifically, a 3-dB reduction of intensity for each doubling of number. Finally, the equal energy hypothesis implies that the temporal spacing should have no effect on the hazard from impulses. In principle, any one or any combination of these derivatives of the equal energy hypothesis could be true.

I. HAZARD INDICATORS

It is the first of these hypotheses that is the main topic of this paper. As part of a series of experiments to explore the critical parameters of impulse noise, Patterson *et al.* (1986) reported a direct comparison of the efficacy of peak pressure and energy in producing TTS, PTS, and hair cell loss. The essence of this study was that exposure impulses were synthesized such that the distribution of acoustic energy across frequency was constant while the peak pressures were different. Figures 1 and 2 show the time histories and Fourier pressure spectra of the two exposure impulses used in this study. The number of impulses was fixed at 100 spaced 3 s apart. The only exposure parameters that varied were the peak pressure and the energy level. Table I shows the exposure conditions for the six groups of chinchilla. These conditions are specified as unweighted sound exposure level (SEL) rather than energy as originally published by Patterson *et al.* (1986) which, as Young (1987) has pointed out, is technically more correct.

TABLE I. Identification of the exposure conditions for the six experimental groups.

Subject group	Stimulus type	Peak pressure (dB SPL)	Unweighted sound exposure level
1	High peak	147	130
2	Low peak	139	130
3	High peak	139	123
4	Low peak	131	122
5	High peak	135	119
6	Low peak	127	119

Figure 3 shows the PTS as a function of sound exposure level. At all sound exposure levels, the low peak wave produced slightly less PTS. In Fig. 4, these data have been replotted as a function of peak pressure. It is clear the differences in PTS for the same peak are much larger. Another way to look at this comparison is to extrapolate the PTS to a "threshold" of PTS. There is about a 2-dB difference in this threshold, based on sound exposure level; there is about a 6-dB difference in the threshold of PTS, based on peak pressure. The results of the histological evaluation of receptor cells is consistent with sound exposure level being a better indicator of cochlear injury potential.

From these results, we can conclude that sound exposure level is a better predictor of both the threshold of hearing loss and the extent of hearing loss than peak pressure.

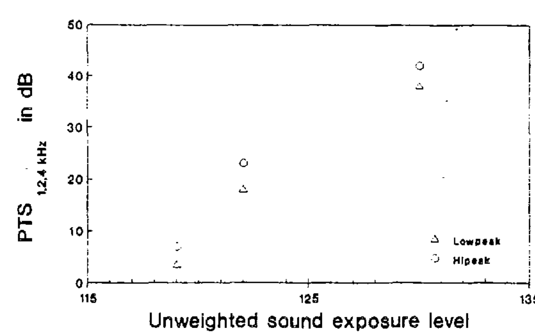

FIG. 3. The mean PTS computed at 1, 2, and 4 kHz as a function of sound exposure level.

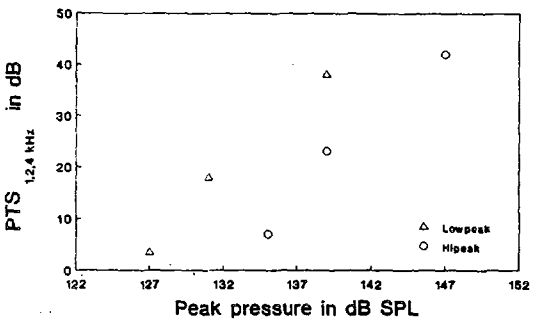

FIG. 4. The mean PTS computed at 1, 2, and 4 kHz as a function of peak pressure level.

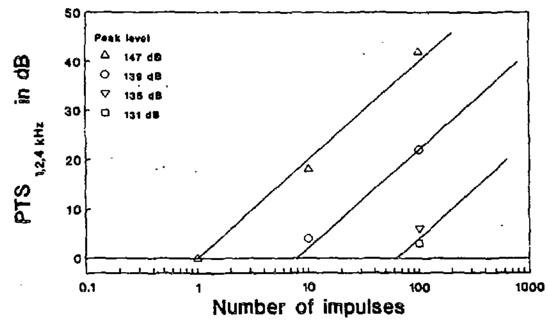

FIG. 5. The mean PTS computed at 1, 2, and 4 kHz as a function of the number of impulses with peak pressure as a parameter. Symbols indicate experimental data; the solid lines have a slope of 2.0 and a spacing of 8 dB.

II. NUMBER/INTENSITY TRADING RULES

The second prediction from an equal energy hypothesis is a number verses intensity trading rule. For impulses with the same spectrum, a 10-fold change in number should be compensated by a 10-dB change in intensity. The trading rule currently in use in the United States (CHABA, 1968) calls for only a 5-dB change of intensity for a 10-fold change in number. These are the two main competitors for number/intensity trading rules.

An extension to the experiments described above (Patterson *et al.*, 1985; Hamernik *et al.*, 1987) involved exposing chinchilla to either ten or one of the high peak impulses at various intensities. When these exposures are combined with the 100 impulse conditions described above, the combinations of intensity and number are shown in Table II.

The PTS resulting from these combinations of intensity and number is shown in Fig. 5. At the higher intensities, the PTS grows linearly with the logarithm of the number of impulses. This growth function is approximately 20 dB of PTS for a 10-fold change in number of impulses. Second, for each intensity, the PTS approaches zero at some number of impulses. These thresholds appear to change 10 dB for 10-fold change in number. The growth rate of PTS as a function of number is not relevant to the issue of whether energy provides an accurate trading rule for number and intensity. It is the change in the threshold of PTS that indicates what this trading rule should be. This becomes more clear when the data are plotted on an SEL axis as in Fig. 6. In this figure, the data all fit a single line reasonably well. This indicates that a 10 dB per 10-fold change in number (energy) trading rule organizes the data from the various intensity and number conditions. The growth of PTS is still 2 dB per 1 dB of energy that is consistent with Fig. 5. In fact, the growth of PTS could be anything within reason. The energy trading rule for number and intensity requires only that the growth rate of PTS be the same for changes in number and for changes in intensity.

TABLE II. Identification of the exposure conditions for the seven experimental groups.

Experimental group	Peak pressure level	Number of impulses	Unweighted sound exposure level
A	131 dB	100	115
B	135 dB	100	119
C	139 dB	10	113
D	139 dB	100	123
E	147 dB	1	110
F	147 dB	10	120
G	147 dB	100	130

III. TEMPORAL SPACING

The third prediction from an energy concept is that temporal spacing should make no difference. This seems implausible on the face of it; however, there is considerable evidence that it does not hold. At very short temporal spacing, middle-ear reflexes come into play. The effect of these reflexes will depend on the spectrum of the impulse and the attenuation function across frequencies. At longer spacing, some recovery may take place between pulses. Between these extremes, there may be a range of temporal spacings over which the hazard potential is independent of the spacing. The discussion of this topic is abbreviated here since Dr. Henderson will discuss it in some detail in a later paper in this symposium.

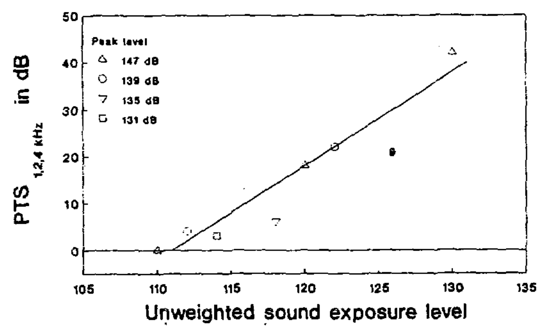

FIG. 6. The mean PTS computed at 1, 2, and 4 kHz as a function of sound exposure level. The solid line has a slope of 2.

IV. CONCLUSIONS

From the review of these studies we can draw the following conclusions.

(1) For impulses with the same spectrum, a spectrally weighted sound exposure level provides a reasonable assessment of the hazard to hearing from a fixed number of impulses. The results discussed here provide no insight into the spectral weighting function that should be used. This is an area where additional studies are required to determine whether a spectral weighting function can be derived that will indicate the hazard from impulses with different spectra.

(2) For numbers of impulses from 1 to 100, sound exposure level provides a reasonable way to trade intensity for number of impulses. A 3-dB reduction in level is required to offset a doubling of the number of impulses.

(3) Conclusions concerning temporal spacing effects will be left to other participants in this symposium.

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